D4.1 technical Improvements to Exoskele-ton (31.7.2016)

Clinical Evaluation of Gait Training with Exoskeleton in Children with Spinal Muscular Atrophy

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Use the table below as an internal changelog. You can delete it before submitting.

Date	Name	Changes/Comments
31.07.2016	Juan Sancho Daniel Sanz-Merodio	First draft

This document describes the improvements of ATLAS 2020 pediatric exoskeleton that allow rehabilitating walking capability, ATLAS2020 offers an innovative effective solution for therapy of children affected by neuromuscular diseases (NMD). ATLAS 2020 would improve the quality of life of these children, giving hope for a better and more independent life.

1 Introduction

ATLAS 2020 is a wearable gait exoskeleton with 10 degrees of freedom (DOF), which allow flexible mobility, for the therapy of children affected by Spinal Muscular Atrophy (SMA). Although it is a rare disease, SMA is the first cause of child mortality, affecting children of both genders, of all races, in all countries. No cure exists for SMA and current treatments are focusing on maintaining the physical state of the patient, and attemting to delay the onset of scoliosis and others important health complicatons (lung disfuction) from non-ambulation. The ATLAS 2020 has been developed for SMA diseases and other similar pathologies in the frame of the European projects KINDER and ExoTrainer. Walking is key for this purpose and ATLAS 2020 provides a better therapy approach through wearable gait exoskeletons. ATLAS 2020 builds over available technology and addresses a new target group and different diseases [2], as current commercial devices are targeted to adult paraplegics. An exoskeleton will have an impact on children's quality of life and life expectancy [5] by allowing affected children to regain muscular activity and mobility. The innovative therapy can reduce the cost to the healthcare treatments, by an improved and personalized therapy. This paper presents the mechanical design of the 10-DOF wearable exoskeleton. In section 2 the rationale behind the mechanical configuration is introduced, and electronics are mentioned. Section 3 describes the physical connection of the exoskeleton with the user, with the basics of the ergonomic design. Section 4 talks about how mechanical design of ATLAS 2020 allows for the balance control and how it works. Finally, section 5 contains the conclusions including proposed future work and research lines.

2 ATLAS 2020 description

ATLAS 2020 structure (figure 1) is divided into two legs joined together with a thoracic junction. All the system has 10-DOF and each leg includes 5-DOF, allowing an approximation to normal human gait. The joints are linked with titanium tubes and the assembly is formed basically by titanium and aluminum.

2.1 Actuated joints

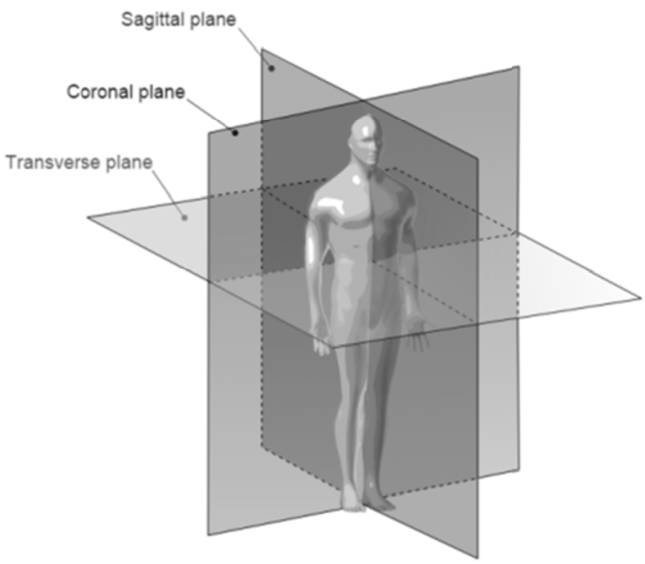

Figure 2: Anatomic planes.

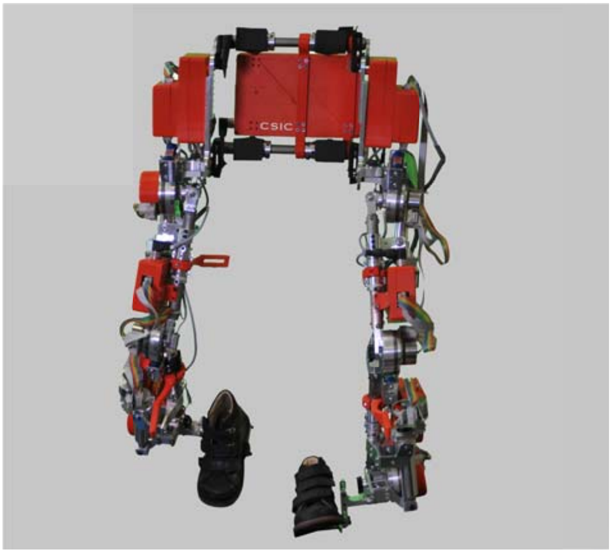

Figure 1: ATLAS 2020 exoskeleton.

These degrees of freedom are those required to provide:

- Hip flexion-extension
- Hip abduction-adduction
- Knee flexion-extension
- Ankle dorsiflexion-plantar flexion
- Ankle eversion-inversion

These joint axes are designed to conform the maximum natural movements of the patient. Three of these joints allow flexion-extension of the hip, knee and dorsiflexion-plantar flexion at the ankle in the sagittal plane (Figure 2). The remaining 2 joints allow movements of abduction/adduction at the hip and eversion/inversion at the ankle in the coronal plane (figure 2).

The choice of these degrees of freedom is determined by the previous study of the needs of the exoskeleton. Actuation in the coronal plane is essential to provide the possibility of obtaining active stability of the gait by compensating center of mass displacement during natural walk.

2.2 Joint ranges

The exoskeleton has mechanical limits that restricts the range of motion at each joint. Mechanical limits have been adapted using published studies of joint ranges movements in healthy subjects and physical requirements of the exoskeleton for a natural gait, a sitting movement and weight transfer movements during dynamically stable locomotion.

Table 1 shows the maximum joint angles of the exoskeleton. It is important to note that operating joint angles can be defined within these ranges of motion by kinematics programming, in case that the patients have retractions or limitations on the mobility of their joints.

Joint	Actuation drive	Degrees
Hip flexion	Rotation drive	110°
Hip extension	Rotation drive	30°
Hip abduction	Linear drive	25°
Hip adduction	Linear drive	10°
Knee flexion	Rotation drive	120°
Knee extension	Rotation drive	0°
Ankle dorsiflexion	Rotation drive	30°
Ankle plantar flexion	Rotation drive	30°
Ankle eversion	Linear drive	16°
Ankle inversion	Linear drive	16°

Table 1: Joint ranges.

2.3 Actuation systems

Two types of actuators have been selected to perform the movement of the 10 DOF. The two actuator types are described below.

2.3.1 Rotation drive

The rotation drives are formed by a gear assembly containing a 70W brushless DC motor, with Hall Effect sensor and quadrature encoder. The gear has a 160:1 transmission ratio. Figure 3 shows this gear motor assembly.

Rotation drive	
Nominal torque (N·m)	20
Maximum torque (N·m)	60
Max. angular speed (RPM)	30
Nominal current (A)	3.21

Table 2: Rotation drive specifications

Figure 3: rotation drive assembly

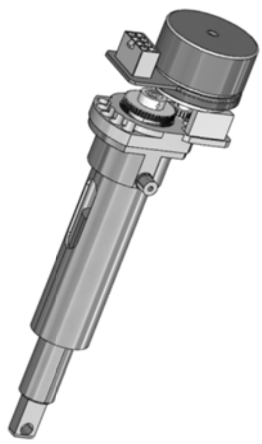

Figure 4: linear drive.

The selected gearing allows the highest reduction in the smallest possible volume guaranteeing a good performance and low power consumption.

2.3.2 Linear drive

Abduction/adduction in the hip joint and eversion/inversion in the ankle joint are implemented by using linear drives. They use a 70W brushless DC motor, with 3:1 pre-stage reduction ratio gearbox and connected to the 10x3 ball output spindle. It has the following characteristics:

Linear drive	
Maximum force (N)	1500
Maximum angular speed in joint (RPM)	30
Nominal current (A)	3.21

Table 3: Linear drive specifications.

The assembly (see figure 4), works as a linear system, connected to a 50 mm arm, to transform the linear movement in rotation at the joint. The selection of the linear system is due to space restrictions at the hipovercoming the difficulty of including a rotation drive in coronal plane very near the point of sagittal rotation.

2.4 Joint impedance control and force sensing

The sagittal plane rotational actuators incorporate a spring ensemble (figure 5), that turns the actuator into a Series elastic actuator (SEA) configuration [3]. This spring ensemble is a system to absorb the shocks, vibrations, and joint dynamics of the user, helping in symptoms such as spasticity.

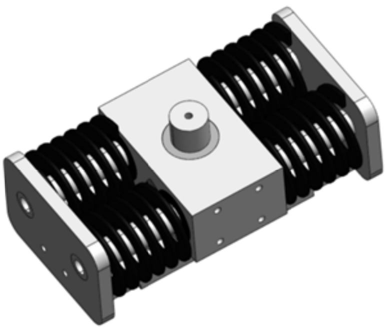

Figure 5: spring ensemble

Figure 6: rotation drive knee joint

Furthermore, using Hooke's law, we get the torque experienced at the joint, as a relation of the distance with the rotation axis and the displacement at the point of applied forces in the elastic system. This has been further detailed in a previous paper by M. Cestari[4]. Figure 6 shows the assembly detail of the rotation system with the elastic ensemble at the knee joint.

2.5 Size regulation system

Figure 7: size regulation by tube system.

The ATLAS 2020 is a pediatric exoskeleton and such as, has to adapt to fast growth of the patient at all stages. It is valid for ages from 3 to 12 years old. All components has been designed thinking on these premises, and users can easily regulate the size of each link. Indeed the regulation size system is one of the keys element in the design of this pediatric exoskeleton. Other critical factors of the design are the parallelism between the comprising tubes of the system, as well as the rigidity and versatility in the change of the exoskeleton size.

Link	Min. (cm)	Max (cm)	Step of size (cm)	System
Trunk depth	8,2	16,6	0,7	Hole
Trunk height	11	21	0,1	Slide
Trunk width	18	34	1	Tube
Upper leg segment	22	46	1	Tube
Lower leg segment	21	45	1	Tube

Table 4: dimensions of size regulation.

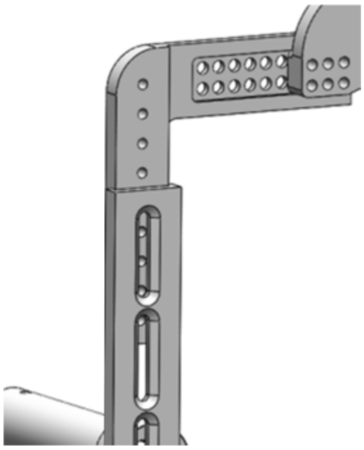

Figure 8: Regulation slide system

Table 4 lists the links that can be adjusted in size, it also lists the minimum and maximum dimensions, and the step size. The tubular system (Figure 7), is used in 3 of 5 types of regulation size systems. These regulations are routinely modified throughout the child's growth. It also allows for a rapid change that can be made in situ, with the patient inside the exoskeleton. The trunk regulation combines the slide with spatially separated positions at fixed steps (see Figure 8).

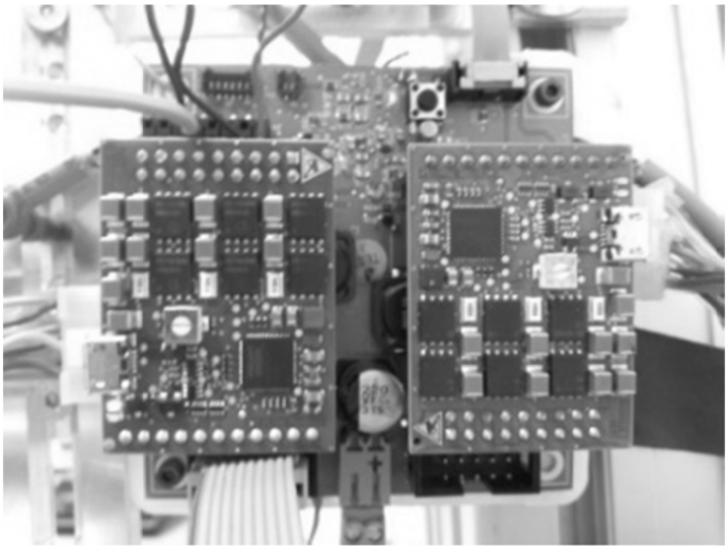

Figure 9: slave controller

2.6 Control electronics

Exoskeleton control is performed by a central master controller and 6 slave controllers (see figure 9). Each slave controller controls 2 motors independently and collects the position information of the controlled joint with an encoder. Thanks to that the space and weight of the control electronics is distributed. The control boxes work with a battery included in each leg. Each module works independently from the others. Electronic modules communicate with the master via I2C in a control loop that is repeated every 2.5ms.

2.7 Weight distribution

ATLAS 2020 exoskeleton has been designed to feature the minimum weight possible. This has been achieved using materials such as titanium and aluminum. The weight is mostly in the joints, because the actuators are the heaviest parts of the exoskeleton. The links manufactured basically from titanium are very light compared with the other components. The next heavier components, are the litium-ion batteries.

Component	Weight (gr)	Units	Weigth sum. (kg)
Rotation drive with elastic set	650	6	3,9
Linear drive	465	4	1,9
Joint connections, bearings and screws	200	6	1,2
Leg link	137	4	0,5
Trunk link	915	1	0,9
Electronic slave board with case	143	6	0,9
Battery pack one per leg	350	2	0,7
Orthotics and physical interface	1000	1	1,0
Master controller with battery and wires	950	1	0.95
		Total (kg)	12

Table 5: weight of components in ATLAS 2020.

Figure 10: clinic trial of ergonomics.

3 Ergonomics

Ergonomics is one of the most important parts of our design. In order to achieve a good gait pattern and avoid harming the patient, the coupling with exoskeleton has to be ergonomically correct. This goal has been achieved by the design described in this paper. In addition, one symptom present in most of the target users is hypotony, and this mean that the users wring out of the normal supports of the exoskeleton. To solve this, the attachment to the exoskeleton is made using a commercial harness, leg supports and orthopedic shoes.

Leg support elements are located, one in front of the tibia and the other behind the femur. In this way the supports help maintain the user standing and the harness secures the trunk in the correct position. The shoes are linked directly to the exoskeleton with a special grip. Figure 10 shows an ergonomically sound user attachment to the exoskeleton.

4 Balance control

The exoskeleton has been designed for stability control in real time. Key design choices to achieve good stability are the number of degrees of freedom, including coronal actuators, and the chosen geometries, as well as the uniform weight distribution throughout the structure. Another decisive parameter in balance control is electronic speed control. It has been reduced to the minimum possible period, enhancing the response speed of actuators and preventing the exoskeleton from falling. The sensors used to control the key parameters for balance are two pressure insoles at the shoe and inertial measurement units (IMU). In addition to calculating the center of mass at all times, the exoskeleton can use algorithms tailored for balance control. The description of these balance control approaches are out of the scope of this paper and will be described in a future publication.

5 Conclusions

An innovative exoskeleton design focusing on adaptability to children growth and ergonomics of SMA affected patients has been proposed. A 10-DOF configuration allowing for complete mobility has been chosen. It has been demonstrated that the proposed structure could easily adapt to varying sizes while respecting performance goals. The capability to perform active balance during walk has been taken into account in the ATLAS 2020 exoskeleton design.

The design of the assembly poses a number of challenges due to the fact that the small size of the exoskeleton increases the risk of collision at the parts. It has been shown that the ergonomics is one of the most critical points for proper gait control of the ATLAS 2020 exoskeleton.. It has been determined that balance control algorithm needs fast electronics for controlling the actuators and avoiding the exoskeleton to fall. .

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